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# RESPONSE CHARACTERISTICS OF DUAL MOSFET GAMMA-RAY SENSORS PRODUCED BY MITEL CORPORATION

by

S. McGowan and R.A. Gravelle

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Nonuniformities in response with photon energy can be attributed to the large amounts of gold in the packages used and measurements indicate that elimination of the gold will lead to good energy response. A reduced response at very high dose rate is alleviated by the addition of capacitance to maintain gate bias during the radiation pulse, but further testing will be required to evaluate the dosimeter performance under relevant field conditions.

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MOSFET
Gamma-Ray Sensor
Individual Dosimeter

National Defence   Défense nationale

# RESPONSE CHARACTERISTICS OF DUAL MOSFET GAMMA-RAY SENSORS PRODUCED BY MITEL CORPORATION

by

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*Protective Sciences Division*

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## ABSTRACT

Radiation-sensitivity measurements were carried out on two batches of dual MOSFET gamma-radiation sensors produced by Mitel Corp and packaged using different procedures by two other commercial firms. Significant differences were observed between the two production batches and also as a result of the difference in packaging. Those from the first Mitel batch packaged by Siltronics Limited were found to be most consistent and should be acceptable as a sensor for the Canadian Forces individual dosimeter.

Nonuniformities in response with photon energy can be attributed to the large amounts of gold in the packages used and measurements indicate that elimination of the gold will lead to good energy response. A reduced response at very high dose rate is alleviated by the addition of capacitance to maintain gate bias during the radiation pulse, but further testing will be required to evaluate the dosimeter performance under relevant field conditions.

## RÉSUMÉ

Nous avons effectué des mesures de sensibilité à la radiation sur deux groupes de détecteurs doubles (MOSFET) produits par la compagnie Mitel. Deux compagnies commerciales les ont assemblés en suivant des processus différents. Nous avons obtenu des résultats divergeants, tant sur les deux groupes de production que sur la difference dans l'assemblage. Nous avons constaté que les détecteurs du premier groupe de Mitel assemblés par la compagnie Siltronics Limitée étaient les plus stables et qu'ils devraient être utilisés comme détecteur individuel pour les Forces Canadiennes.

Nous attribuons le manque d'uniformité dans la réponse avec l'énergie photonique à la trop grande quantité d'or dans l'assemblage. En éliminant cet or, les tests nous indiquent une nette amélioration du rendement énergétique. Si nous ajoutons un condensateur pour maintenir la tension du discriminateur pendant l'impulsion de radiation, nous minimisons l'effet de réduction de la réponse dû à un très haut taux d'irradiation. Cependant, nos devrons continuer les tests afin d'évaluer le rendement des détecteurs sous des conditions pertinentes sur place.

## 1. Introduction

Radiation damage to MOS devices in the form of charge trapping in the oxide layer was recognized and quantified over twenty years ago. Much of the early research in this area was directed towards reducing this effect to produce radiation-hard devices, but as early as 1970 the radiation effects on MOS transistors (MOSFETs) and capacitors were being used for dosimetry purposes (Ref (1 to 5)).

Recent development of the MOSFET gamma-radiation sensor (Ref (6 to 9)) has resulted in a sensor capable of measuring doses as low as 1 cGy. This sensor consists of a dual p-channel MOSFET with a thick oxide layer and a very low initial imbalance. A bias voltage is applied to one gate of the MOSFET to enhance its radiation sensitivity while the other gate is unbiased and used as a reference, as suggested in Ref (5). This sensor is being used in the individual dosimeter under development for the Canadian Forces.

To obtain an accurate reading of the gamma-ray dose with the proposed Canadian Forces dosimeter, these sensors must be reproducible with predictable sensitivity. Errors introduced because of non-uniform photon energy response, variation in response with dose rate and changes in the dosimeter reading with time after irradiation must be kept to a minimum. This report investigates some of the packaging parameters which affect the sensitivity of the MOSFET sensors fabricated by Mitel Corp under a DREO contract with Pacific Microcircuits Limited.

## 2. Packaging Variations

MOSFET sensors were produced in two production batches at Mitel. These devices use silicon gates rather than metal gates, so maybe they should be called "SOSFETs", but the more conventional label is retained in this report. Three oxide-layer thicknesses (0.3, 0.4 and 0.5 $\mu$m) were produced in the first batch while only 0.4-$\mu$m MOSFETs were made in the second batch. The sensors from the first batch were packaged only at Siltronics Limited using dual-in-line ceramic packages. Most of the packaging for the second batch was done at Pantronics using cerdip packages, but some of these were also packaged at Siltronics using the same packages as for the first batch. The Pantronics packages were all hermetically sealed as were most of the Siltronics packages but some of the latter were left unsealed for testing purposes. Some packages, from both companies were opened and tested with the chips exposed to the atmosphere. Some of the chips were potted in various materials to study the effect of the package on the energy response and some of the sensors were heat treated before testing.

3. Summary of Measurements of MOSFET Sensors from the First Mitel Production Batch

Detailed results of the measurements of the sensors from the first production batch at Mitel are given in Ref (10). A summary of these results is given below.

These dual MOSFETs were found to be well balanced when measured both on the wafer and after packaging. About 70% were found to have initial offsets of less than 5 mV, which corresponds to about 3 cGy for the 0.4-$\mu$m sensors used differentially with biases of 0 and +5.6 V. Pre-selection could yield a large fraction of devices with initial offsets less than one or two cGy.

For the 0.4-$\mu$m MOSFETs the unbiased sensitivity was found to be about 0.6 mV/cGy for $^{60}$Co gamma rays. For the same radiation, the differential response with +5.6 V applied to the biased gate was observed to be about 1.9 mV/cGy when measured 24 h after exposure. Increasing the bias from 5.6 to 9.3 V gave an increase in response of about 40% as did increasing the bias from 3.3 to 5.6 V. Increasing the oxide-layer thickness from 0.3 to 0.4 and from 0.4 to 0.5 $\mu$m gave increases in response of about 50%.

The sensor readings were observed to increase following irradiation in a predictable manner. This is shown in Figs 1 and 2 for 0.4-$\mu$m sensors. Note the measurements were made in terms of exposure in Roentgens (R). For $^{60}$Co, which was used for these measurements, 1 R is equivalent to 0.96 cGy (tissue). An increase of about 5% in the differential reading was observed in the first 24 h and an additional increase of a few % in the next few weeks, after which a slow decrease was found. One year after irradiation the reading was within a few % of the 24-h reading. The other thicknesses showed similar behaviour.

The effect of applying bias to the gates of unirradiated sensors was very small, but the irradiated devices showed voltage shifts corresponding to about 1% change in sensitivity when the bias was removed or applied, the larger readings being found with no bias.

Measurements over doses from 10 to 1000 cGy indicated a decrease in the 24-h differential sensitivity of about 2%.

A dose-rate dependence was found when doses of 1 Gy or more were delivered in short pulses of 100 $\mu$s of less (Ref (11)). The response of the biased half of the MOSFET was found to decrease with increasing dose per pulse but the response of the unbiased half showed little change. The loss in response was alleviated by adding capacitance greater than 1 nF between the biased gate and the substrate. It was concluded that the loss in response was due to a drop in the bias voltage during the radiation pulse.

Measurements at DREO of the response to 140-keV x-rays showed an increase by a factor of 2 relative to $^{60}$Co gammas (1.25 MeV). More detailed measurements by Kronenberg (12) showed that the response peaks between 50 and 100 keV where it is about 5 times the response to $^{137}$Cs

DRIFT IN RADIATION SENSITIVITY

BOARD# 41 WAFER# 17 THICKNESS .4 MICRON

INITIAL READING # 2 WAS ON DAY 166.358
IRRADIATION # 1 WAS ON DAY 166.449
EXPOSURE IN R 205.7
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 3

AVERAGE INITIAL READINGS :
GATE-SOURCE-VOLTAGE = 2.9518 ( .0682) V DIFF VOLTAGE = .0014 ( .0027) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 41
NUMBER OF DEVICES IN AVERAGE = 20

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.5070 ( .0440) | .6227 ( .0113) | 1.8842 ( .0334) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 41

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .042 | .9453 ( .0138) | .9188 ( .0128) | .9541 ( .0146) |
| .164 | .9644 ( .0151) | .9472 ( .0148) | .9701 ( .0156) |
| 1.005 | 1.0000 ( .0176) | 1.0000 ( .0182) | 1.0000 ( .0177) |
| 1.977 | 1.0136 ( .0184) | 1.0215 ( .0196) | 1.0110 ( .0184) |
| 3.929 | 1.0282 ( .0187) | 1.0451 ( .0202) | 1.0226 ( .0187) |
| 6.914 | 1.0397 ( .0187) | 1.0650 ( .0206) | 1.0313 ( .0185) |
| 9.914 | 1.0436 ( .0187) | 1.0678 ( .0209) | 1.0356 ( .0184) |
| 17.084 | 1.0535 ( .0180) | 1.0845 ( .0193) | 1.0433 ( .0181) |
| 36.216 | 1.0635 ( .0172) | 1.1013 ( .0186) | 1.0511 ( .0173) |
| 43.113 | 1.0636 ( .0173) | 1.1045 ( .0196) | 1.0500 ( .0169) |
| 50.982 | 1.0672 ( .0173) | 1.1203 ( .0203) | 1.0497 ( .0168) |
| 59.946 | 1.0681 ( .0167) | 1.1247 ( .0190) | 1.0494 ( .0165) |
| 73.107 | 1.0696 ( .0168) | 1.1313 ( .0195) | 1.0492 ( .0165) |
| 86.012 | 1.0735 ( .0162) | 1.1490 ( .0191) | 1.0485 ( .0159) |
| 94.979 | 1.0591 ( .0162) | 1.0899 ( .0181) | 1.0490 ( .0160) |
| 111.994 | 1.0624 ( .0160) | 1.1003 ( .0175) | 1.0499 ( .0160) |
| 133.026 | 1.0605 ( .0156) | 1.0940 ( .0168) | 1.0495 ( .0159) |
| 143.026 | 1.0578 ( .0156) | 1.0880 ( .0170) | 1.0479 ( .0158) |
| 161.164 | 1.0626 ( .0154) | 1.1132 ( .0236) | 1.0459 ( .0163) |
| 188.994 | 1.0602 ( .0151) | 1.1007 ( .0165) | 1.0468 ( .0154) |
| 220.108 | 1.0610 ( .0151) | 1.1051 ( .0168) | 1.0465 ( .0153) |
| 244.985 | 1.0594 ( .0148) | 1.1020 ( .0160) | 1.0454 ( .0152) |
| 280.995 | 1.0560 ( .0151) | 1.0913 ( .0165) | 1.0443 ( .0152) |
| 322.099 | 1.0576 ( .0150) | 1.1020 ( .0167) | 1.0429 ( .0150) |
| 436.081 | 1.0580 ( .0145) | 1.1063 ( .0163) | 1.0420 ( .0146) |

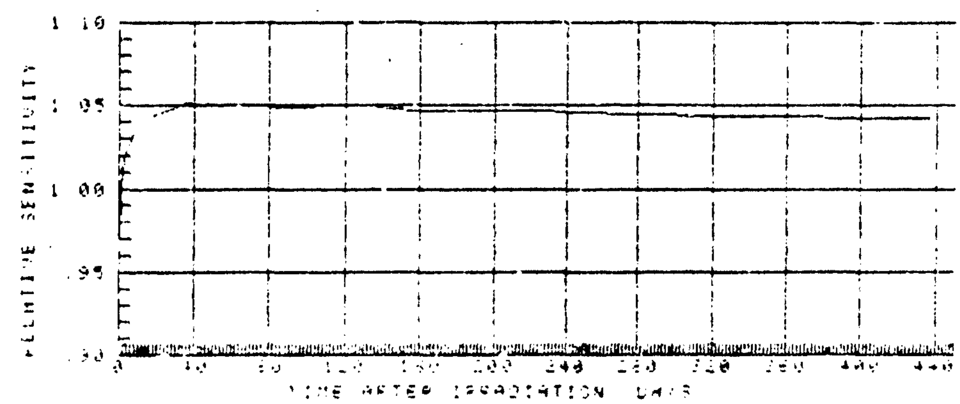


**Figure 1: Measured sensitivity as a function of time after irradiation for devices from the first Mitel production batch. The bias voltage was applied during irradiation only for this board, but was retained after irradiation for all the other figures in this report. The standard deviations are given in parenthesis.**

DRIFT IN RADIATION SENSITIVITY

BOARD# 1 WAFER# 18 THICKNESS .4 MICRON

INITIAL READING # 2 WAS ON DAY 99.371
IRRADIATION # 1 WAS ON DAY 99.448
EXPOSURE IN R 206.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 3

AVERAGE INITIAL READINGS :
EXCLUDING # 3
GATE-SOURCE-VOLTAGE = 2.8781 ( .0210) V DIFF VOLTAGE = -.0008 ( .0087) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 1
NUMBER OF DEVICES IN AVERAGE = 19

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.4913 ( .0716) | .6184 ( .0059) | 1.8729 ( .0190) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 1

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .005 | .9344 ( .0060) | .8854 ( .0064) | .9506 ( .0077) |
| .050 | .9554 ( .0062) | .9172 ( .00[illegible]) | .9680 ( .0079) |
| .197 | .9738 ( .0081) | .9500 ( .0080) | .9817 ( .0099) |
| .925 | 1.0000 ( .0067) | 1.0003 ( .0095) | 1.0000 ( .0101) |
| 1.221 | 1.0047 ( .0091) | 1.0174 ( .0105) | 1.0005 ( .0106) |
| 3.917 | 1.0232 ( .0096) | 1.0439 ( .0110) | 1.0164 ( .0111) |
| 4.944 | 1.0278 ( .0090) | 1.0638 ( .0118) | 1.0159 ( .0106) |
| 6.923 | 1.0314 ( .0089) | 1.0777 ( .0108) | 1.0161 ( .0103) |
| 11.136 | 1.0405 ( .0090) | 1.0949 ( .0104) | 1.0225 ( .0105) |
| 13.938 | 1.0432 ( .0089) | 1.1040 ( .0107) | 1.0231 ( .0107) |
| 20.868 | 1.0452 ( .0094) | 1.1070 ( .0108) | 1.0248 ( .0111) |
| 27.941 | 1.0474 ( .0088) | 1.1158 ( .0097) | 1.0249 ( .0106) |
| 35.124 | 1.0477 ( .0091) | 1.1162 ( .0107) | 1.0251 ( .0114) |
| 40.911 | 1.0472 ( .0080) | 1.1200 ( .0107) | 1.0231 ( .0101) |
| 48.092 | 1.0485 ( .0080) | 1.1261 ( .0098) | 1.0229 ( .0102) |
| 54.888 | 1.0491 ( .0135) | 1.1275 ( .0104) | 1.0233 ( .0172) |
| 61.909 | 1.0487 ( .0132) | 1.1262 ( .0100) | 1.0231 ( .0171) |
| 69.949 | 1.0470 ( .0129) | 1.1271 ( .0090) | 1.0205 ( .0169) |
| 81.018 | 1.0376 ( .0126) | 1.1158 ( .0093) | 1.0118 ( .0164) |
| 103.163 | 1.0387 ( .0125) | 1.1159 ( .0094) | 1.0132 ( .0164) |
| 117.993 | 1.0402 ( .0122) | 1.1283 ( .0099) | 1.0111 ( .0160) |
| 140.014 | 1.0448 ( .0125) | 1.1510 ( .0097) | 1.0098 ( .0163) |
| 161.910 | 1.0331 ( .0143) | 1.0906 ( .0094) | 1.0141 ( .0186) |
| 189.013 | 1.0325 ( .0122) | 1.1055 ( .0085) | 1.0083 ( .0159) |
| 209.975 | 1.0262 ( .0128) | 1.0845 ( .0101) | 1.0070 ( .0175) |
| 228.147 | 1.0319 ( .0119) | 1.1142 ( .0082) | 1.0047 ( .0159) |
| 236.240 | 1.0321 ( .0122) | 1.1160 ( .0082) | 1.0045 ( .0162) |

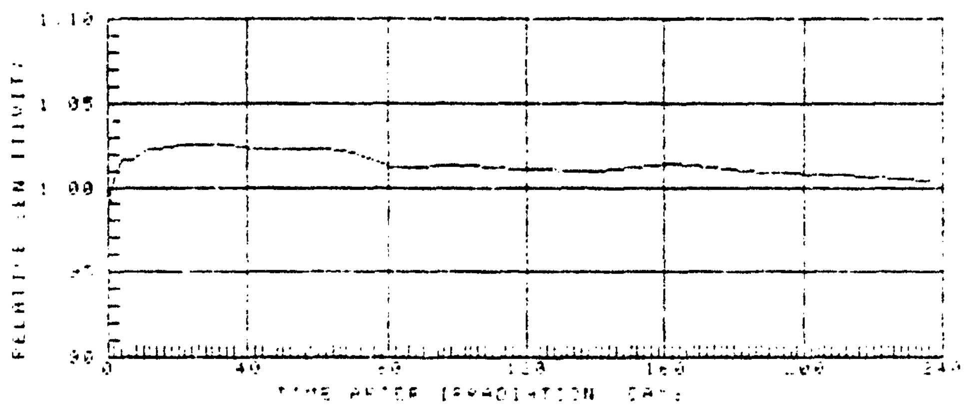


**Figure 2: Measured sensitivity as a function of time after irradiation for devices from the first Mitel batch. The device in Socket 3 was excluded because of a fault which developed near the end of these measurements.**

gammas (0.66 MeV). This large response at low photon energies was attributed to the large amount of gold plating in the ceramic package near the MOSFET chip. This is discussed further in Sec 9 of this report.

## 4. Difference between Sensors from First and Second Mitel Production Batches

The first sensors from the second Mitel batch were packaged by Pantronics, primarily for economic reasons but also to check the dependence of performance on packaging. It was not anticipated that the difference in packaging would appreciably affect the performance. However, measurements made under the same conditions as for the the sensors from the first batch, packaged by Siltronics, showed a lower sensitivity (1.6 mV/cGy at 24 h) and generally little drift in reading for several days after irradiation. A typical average drift pattern is shown in Fig 3. After several days most of the readings gradually drifted upward with considerable variation from device to device, as shown in Fig 4 by the plots for three individual devices.

Subsequently, some sensors from the second batch were packaged at Siltronics along with some more sensors from the first batch. Results are plotted in Figs 5 and 6. Comparison of Figs 3 and 5 indicate that there are large differences which can be attributed to differences in the packages and/or packaging procedures used at Siltronics and Pantronics. However, the differences between Figs 5 and 6 indicate that there are also significant differences between devices from the two Mitel batches. Initial sensitivities are about the same but the post-irradiation drift is faster for the second batch, reaching almost 2.2 mV/cGy 24 h after irradiation and peaking a few % higher about 1 week later. The differences between sensors from the two Mitel batches are about 10%, depending on the time after irradiation. Those from the first batch are the more acceptable because of the smaller overall variation in reading with time.

## 5. Sensitivity of Sensors in Unsealed Packages

Some of the sensors packaged at Siltronics were left unsealed and some of the hermetically-sealed packages from both companies were opened.

When the Siltronics-packaged sensors were irradiated a few minutes after they were opened, they showed most of the increase in reading observed when they were kept sealed. However, after being opened for more than a day before irradiation, the readings for devices from the first Mitel batch were observed to increase more slowly as shown in Fig 7. A similar response was observed for these sensors which were mounted in the unsealed packages. The 24-h sensitivity is lower than for the sealed sensors but the post-irradiation drift is very small for several months.

The unsealed devices from the second Mitel batch (and devices from this batch which were irradiated after being open for three days) showed a much larger drift than devices from the first batch. This is shown in Fig 8 which resembles the drift of the Pantronics-packaged sensors of Fig 3. Opening the Pantronics packages did not appear to alter the response appreciably as seen by comparison of Fig 9 (for two devices only) with Figs 3 and 4.

DRIFT IN RADIATION SENSITIVITY

BOARD# 27 WAFER# 100 THICKNESS .4 MICRON

INITIAL READING # 4 WAS ON DAY 320.574
IRRADIATION # 1 WAS ON DAY 321.560
EXPOSURE IN R 200.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 5

AVERAGE INITIAL READINGS :
GATE-SOURCE-VOLTAGE = 3.0392 ( .2035) V DIFF VOLTAGE = .0030 ( .0030) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 27
NUMBER OF DEVICES IN AVERAGE = 20

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.0331 ( .0245) | .5058 ( .0169) | 1.5273 ( .0165) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 27

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .010 | .9887 ( .0088) | .9739 ( .0186) | .9936 ( .0108) |
| .989 | 1.0000 ( .0121) | 1.0000 ( .0334) | 1.0000 ( .0108) |
| 1.832 | 1.0105 ( .0184) | 1.0276 ( .0465) | 1.0048 ( .0126) |
| 3.015 | 1.0245 ( .0286) | 1.0572 ( .0560) | 1.0136 ( .0212) |
| 5.800 | 1.0517 ( .0444) | 1.0972 ( .0589) | 1.0367 ( .0411) |
| 8.890 | 1.0757 ( .0510) | 1.1258 ( .0562) | 1.0591 ( .0510) |
| 13.889 | 1.1053 ( .0525) | 1.1568 ( .0509) | 1.0882 ( .0553) |
| 21.009 | 1.1366 ( .0505) | 1.2022 ( .0485) | 1.1149 ( .0540) |
| 33.808 | 1.1539 ( .0449) | 1.1824 ( .0398) | 1.1445 ( .0494) |
| 44.997 | 1.1643 ( .0408) | 1.1873 ( .0365) | 1.1567 ( .0451) |
| 56.830 | 1.1721 ( .0379) | 1.1975 ( .0353) | 1.1637 ( .0417) |
| 69.045 | 1.1807 ( .0356) | 1.2204 ( .0354) | 1.1676 ( .0390) |
| 103.990 | 1.1863 ( .0317) | 1.2164 ( .0331) | 1.1764 ( .0344) |
| 125.833 | 1.1844 ( .0300) | 1.1994 ( .0323) | 1.1794 ( .0326) |
| 142.068 | 1.1821 ( .0287) | 1.2026 ( .0315) | 1.1753 ( .0309) |
| 166.980 | 1.1861 ( .0280) | 1.2146 ( .0325) | 1.1767 ( .0299) |
| 198.896 | 1.1884 ( .0273) | 1.2318 ( .0327) | 1.1741 ( .0290) |
| 281.025 | 1.1936 ( .0273) | 1.2330 ( .0317) | 1.1805 ( .0294) |

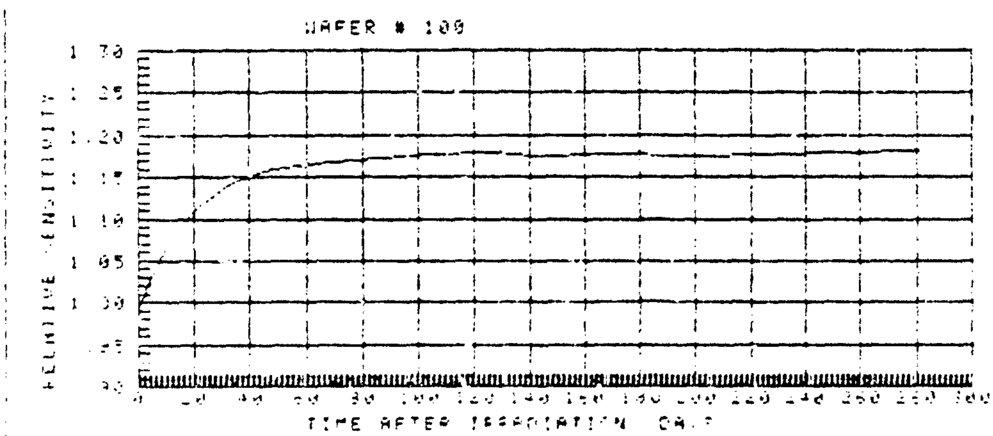


**Figure 3: Measured sensitivity as a function of time after irradiation for devices from the second Mitel batch packaged by Pantronics. Note the low 24-h sensitivity compared with Figs 1 and 2.**

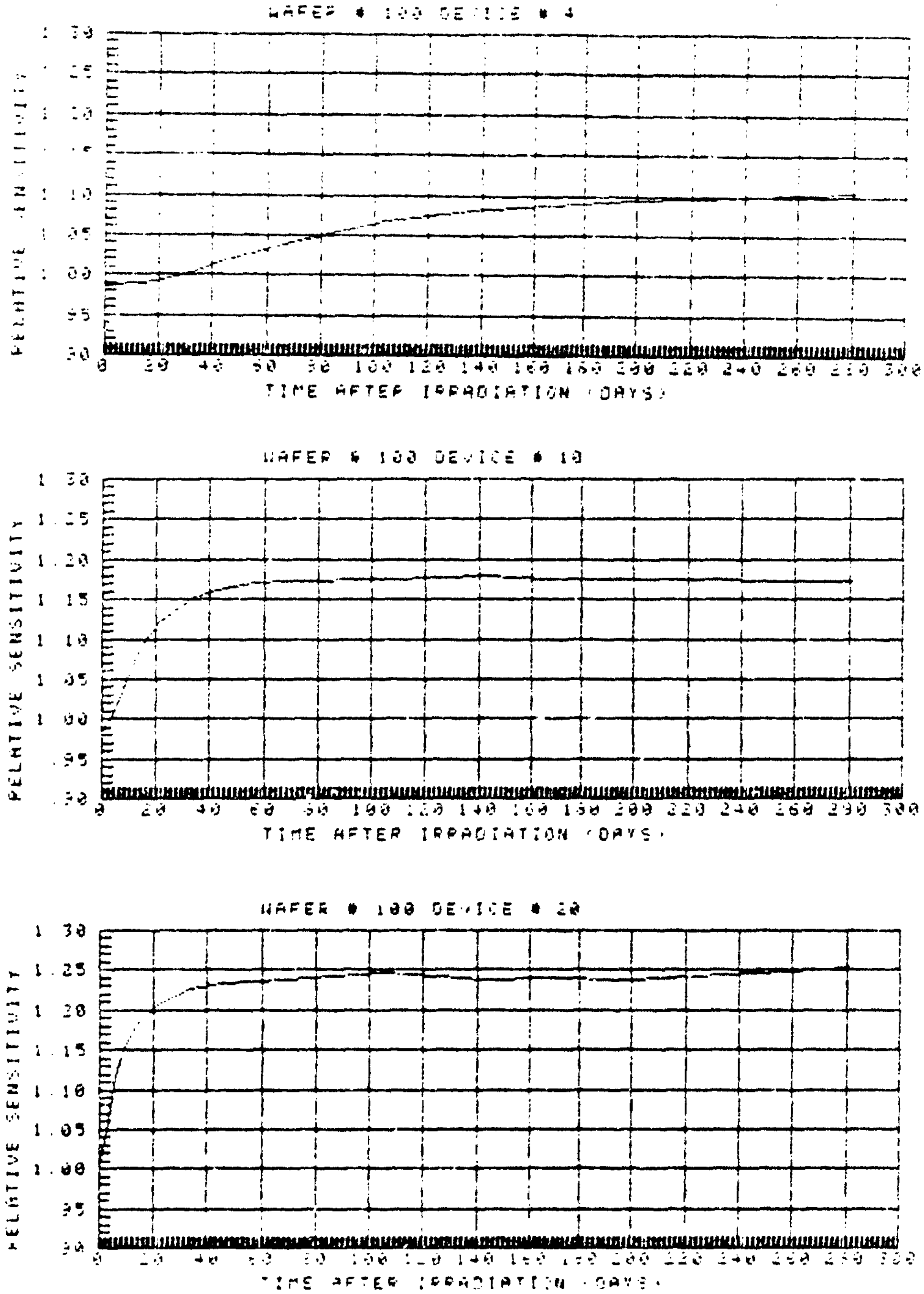


Figure 4: Measured sensitivity as a function of time after irradiation for three individual devices on board #27 of Fig 3. Note the large variations in the drift pattern. This leads to the fairly large standard deviations in Fig 3 a few weeks after irradiation.

DRIFT IN RADIATION SENSITIVITY

BOARD# 11 WAFER# 113 THICKNESS .4 MICRON

INITIAL READING # 7 WAS ON DAY 384.344
IRRADIATION # 1 WAS ON DAY 384.368
EXPOSURE IN R 200.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 8

AVERAGE INITIAL READINGS :

GATE-SOURCE-VOLTAGE = 2.9770 ( .1360) V DIFF VOLTAGE = .0024 ( .0013) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 11
NUMBER OF DEVICES IN AVERAGE = 8

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.8040 ( .0392) | .7058 ( .0153) | 2.0982 ( .0289) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 11

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .003 | .8613 ( .0170) | .8816 ( .0249) | .8545 ( .0161) |
| .038 | .9181 ( .0170) | .9261 ( .0233) | .9155 ( .0167) |
| .175 | .9625 ( .0162) | .9626 ( .0218) | .9625 ( .0163) |
| .299 | .9729 ( .0152) | .9730 ( .0223) | .9729 ( .0148) |
| .985 | 1.0000 ( .0140) | 1.0000 ( .0217) | 1.0000 ( .0138) |
| 1.992 | 1.0115 ( .0140) | 1.0112 ( .0216) | 1.0115 ( .0137) |
| 3.106 | 1.0133 ( .0118) | 1.0197 ( .0219) | 1.0111 ( .0114) |
| 6.073 | 1.0254 ( .0110) | 1.0391 ( .0216) | 1.0208 ( .0105) |
| 9.102 | 1.0234 ( .0098) | 1.0348 ( .0210) | 1.0196 ( .0089) |
| 13.081 | 1.0175 ( .0094) | 1.0373 ( .0196) | 1.0108 ( .0093) |
| 21.033 | 1.0174 ( .0077) | 1.0380 ( .0185) | 1.0104 ( .0070) |
| 27.175 | 1.0122 ( .0084) | 1.0409 ( .0182) | 1.0026 ( .0083) |
| 35.305 | 1.0066 ( .0084) | 1.0390 ( .0179) | .9957 ( .0091) |
| 62.218 | .9999 ( .0088) | 1.0403 ( .0176) | .9864 ( .0103) |
| 104.091 | .9858 ( .0077) | 1.0400 ( .0168) | .9675 ( .0087) |
| 111.068 | .9837 ( .0075) | 1.0399 ( .0181) | .9648 ( .0083) |
| 136.082 | .9843 ( .0059) | 1.0464 ( .0172) | .9634 ( .0067) |
| 161.170 | .9762 ( .0088) | 1.0509 ( .0181) | .9511 ( .0103) |
| 177.023 | .9736 ( .0086) | 1.0540 ( .0174) | .9466 ( .0102) |
| 270.015 | .9687 ( .0080) | 1.0445 ( .0169) | .9431 ( .0093) |

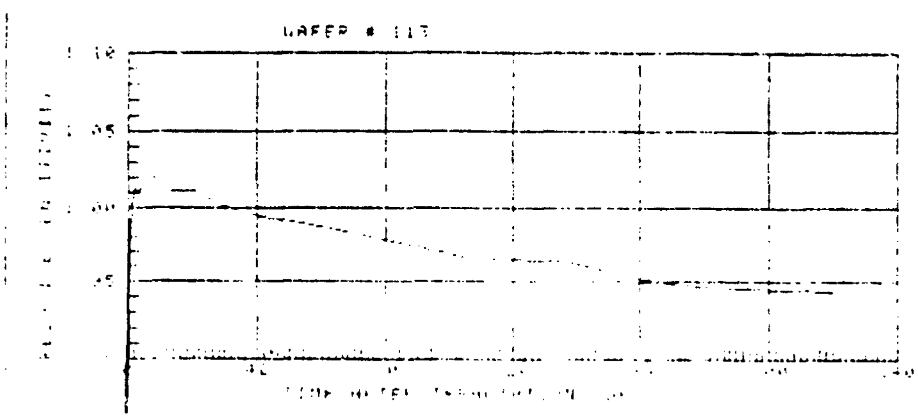


Figure 5: Measured sensitivity as a function of time after irradiation for devices from the second Mitel batch packaged at Siltronics. Note the much faster increase in reading and the higher 24-h sensitivity than for the Panatronics-packaged devices of Figs 3 and 4.

DRIFT IN RADIATION SENSITIVITY

BOARD# 33 WAFER# 17 THICKNESS .4 MICRON

INITIAL READING # 21 WAS ON DAY 460.345
IRRADIATION # 2 WAS ON DAY 461.346
EXPOSURE IN R 202.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.5
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 22

AVERAGE INITIAL READINGS :
GATE-SOURCE-VOLTAGE = 3.1181 ( .2784) V DIFF VOLTAGE = .0002 ( .0043) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 33
NUMBER OF DEVICES IN AVERAGE = 20

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.4605 ( .0293) | .6077 ( .0059) | 1.8528 ( .0251) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 33

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .003 | .9361 ( .0099) | .8850 ( .0084) | .9528 ( .0115) |
| .021 | .9491 ( .0099) | .9050 ( .0078) | .9636 ( .0116) |
| .140 | .9697 ( .0104) | .9438 ( .0083) | .9782 ( .0122) |
| .289 | .9796 ( .0107) | .9630 ( .0086) | .9851 ( .0124) |
| .978 | 1.0000 ( .0119) | 1.0000 ( .0097) | 1.0000 ( .0135) |
| 1.971 | 1.0114 ( .0125) | 1.0171 ( .0105) | 1.0095 ( .0141) |
| 3.011 | 1.0167 ( .0130) | 1.0300 ( .0114) | 1.0124 ( .0147) |
| 6.087 | 1.0308 ( .0148) | 1.0681 ( .0148) | 1.0185 ( .0160) |
| 14.184 | 1.0428 ( .0158) | 1.0807 ( .0146) | 1.0303 ( .0173) |
| 22.035 | 1.0490 ( .0161) | 1.0968 ( .0147) | 1.0333 ( .0177) |
| 27.219 | 1.0495 ( .0164) | 1.1003 ( .0146) | 1.0328 ( .0180) |
| 34.261 | 1.0508 ( .0169) | 1.1047 ( .0151) | 1.0331 ( .0183) |
| 43.048 | 1.0567 ( .0181) | 1.1169 ( .0159) | 1.0370 ( .0197) |
| 59.102 | 1.0573 ( .0167) | 1.1241 ( .0161) | 1.0355 ( .0178) |
| 142.116 | 1.0600 ( .0182) | 1.1314 ( .0168) | 1.0366 ( .0196) |
| 167.040 | 1.0601 ( .0184) | 1.1425 ( .0183) | 1.0331 ( .0194) |

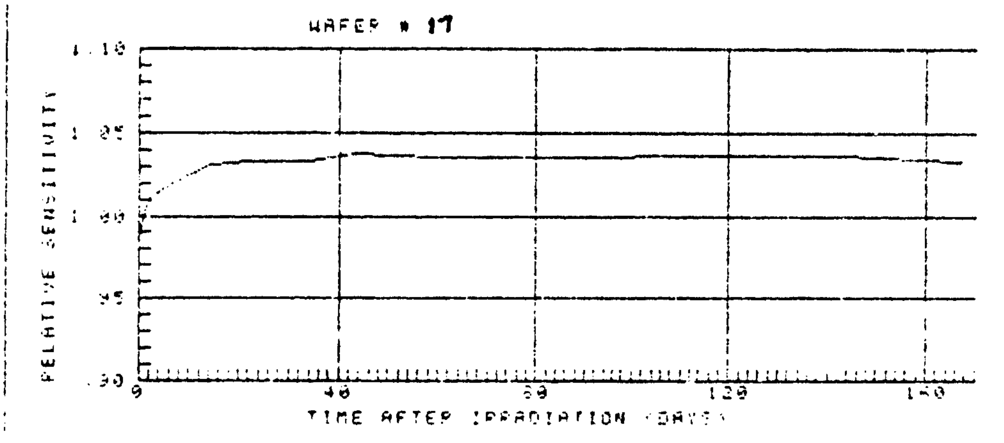


**Figure 6: Measured sensitivity as a function of time after irradiation for devices from the first Mitel batch packaged and irradiated along with those in Fig 5. Note the agreement with earlier measurcments of Figs 1 and 2 and the differences from Figure 5, showing the different characteristics of the two Mitel batches.**

DRIFT IN RADIATION SENSITIVITY

BOARD# 7 WAFER# 17 THICKNESS .4 MICRON

INITIAL READING # 18 WAS ON DAY 491.358
IRRADIATION # 2 WAS ON DAY 491.383
EXPOSURE IN R 201.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 19

AVERAGE INITIAL READINGS :
GATE-SOURCE-VOLTAGE = 3.1105 ( .1480) V DIFF VOLTAGE = .0006 ( .0002) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 7
NUMBER OF DEVICES IN AVERAGE = 2

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.2683 ( .0022) | .5279 ( .0104) | 1.7404 ( .0126) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 7

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .004 | .9902 ( .0052) | .9736 ( .0057) | .9952 ( .0085) |
| .022 | .9910 ( .0034) | .9684 ( .0099) | .9979 ( .0074) |
| .080 | .9968 ( .0016) | .9873 ( .0156) | .9997 ( .0068) |
| .164 | .9974 ( .0014) | .9896 ( .0170) | .9997 ( .0070) |
| 1.013 | 1.0000 ( .0010) | 1.0000 ( .0198) | 1.0000 ( .0072) |
| 4.166 | 1.0049 ( .0011) | 1.0174 ( .0203) | 1.0012 ( .0076) |
| 29.067 | 1.0405 ( .0074) | 1.1173 ( .0042) | 1.0171 ( .0109) |
| 54.154 | 1.0543 ( .0060) | 1.1494 ( .0042) | 1.0254 ( .0091) |
| 62.072 | 1.0552 ( .0076) | 1.1588 ( .0042) | 1.0237 ( .0113) |
| 70.019 | 1.0573 ( .0076) | 1.1654 ( .0042) | 1.0245 ( .0113) |
| 102.014 | 1.0646 ( .0063) | 1.1748 ( .0033) | 1.0312 ( .0092) |
| 118.071 | 1.0613 ( .0083) | 1.1664 ( .0033) | 1.0294 ( .0119) |
| 133.012 | 1.0622 ( .0083) | 1.1673 ( .0042) | 1.0303 ( .0121) |

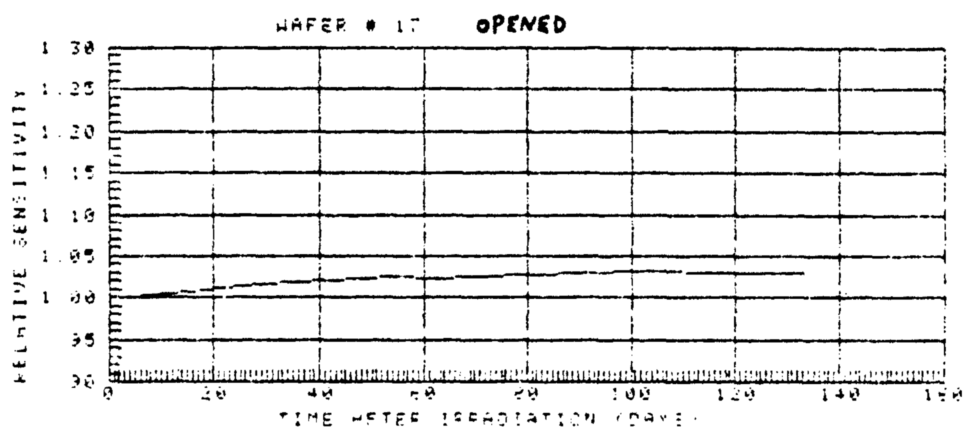


Figure 7: Measured sensitivity as a function of time after irradiation for two devices from the first Mitel batch irradiated 24 h after their sealed packages were opened. Note the low drift in reading during the first day compared with the sealed devices of Figs 1,2 and 6.

DRIFT IN RADIATION SENSITIVITY

BOARD# 26 WAFER# 119 THICKNESS .4 MICRON

INITIAL READING # 22 WAS ON DAY 467.325
IRRADIATION # 2 WAS ON DAY 467.335
EXPOSURE IN R 201.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 23

AVERAGE INITIAL READINGS :
GATE-SOURCE-VOLTAGE = 2.7571 ( .0734) V DIFF VOLTAGE = .0022 ( .0020) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 26
NUMBER OF DEVICES IN AVERAGE = 7

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.0852 ( .0144) | .5031 ( .0078) | 1.5820 ( .0090) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 26

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .005 | .9941 ( .0058) | .9891 ( .0101) | .9957 ( .0056) |
| .021 | .9977 ( .0065) | .9966 ( .0126) | .9980 ( .0058) |
| .096 | .9995 ( .0069) | 1.0008 ( .0157) | .9990 ( .0057) |
| .173 | .9997 ( .0069) | 1.0014 ( .0157) | .9991 ( .0057) |
| .999 | 1.0000 ( .0069) | 1.0000 ( .0155) | 1.0000 ( .0057) |
| 2.073 | 1.0013 ( .0069) | 1.0030 ( .0150) | 1.0008 ( .0058) |
| 8.193 | 1.0454 ( .0128) | 1.1081 ( .0198) | 1.0254 ( .0114) |
| 16.045 | 1.0973 ( .0167) | 1.1661 ( .0166) | 1.0754 ( .0178) |
| 21.230 | 1.1176 ( .0140) | 1.1808 ( .0174) | 1.0975 ( .0142) |
| 28.271 | 1.1429 ( .0152) | 1.1927 ( .0170) | 1.1271 ( .0164) |
| 37.061 | 1.1690 ( .0122) | 1.2175 ( .0156) | 1.1535 ( .0127) |
| 53.121 | 1.2154 ( .0143) | 1.2541 ( .0166) | 1.2030 ( .0158) |
| 137.266 | 1.2693 ( .0154) | 1.3147 ( .0149) | 1.2549 ( .0186) |
| 161.042 | 1.2678 ( .0160) | 1.3259 ( .0167) | 1.2494 ( .0192) |

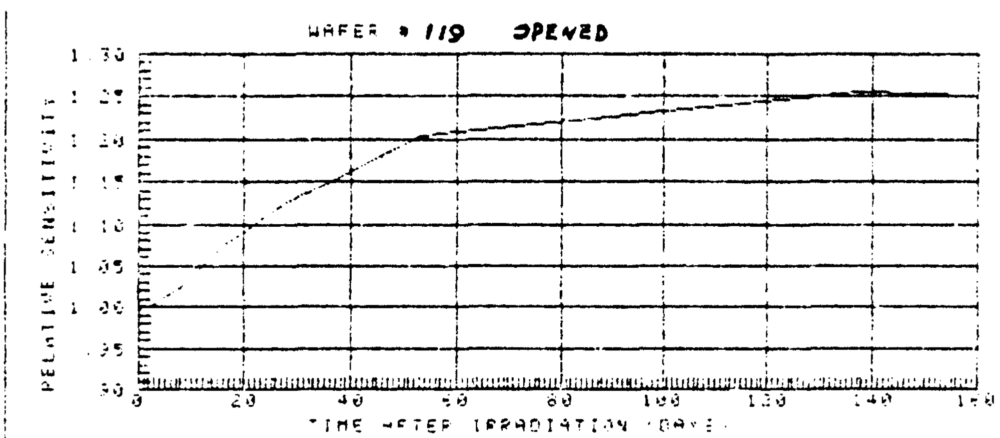


Figure 8: Measured sensitivity as a function of time after irradiation for devices from the second Mitel batch which were packaged by Siltronics and irradiated 3 days after their sealed packages were opened. This resembles the response for the Pantronics-packaged sensors of Figure 3.

DRIFT IN RADIATION SENSITIVITY

BOARD# 7 WAFER# 100 THICKNESS .4 MICRON

INITIAL READING # 18 WAS ON DAY 491.358
IRRADIATION # 2 WAS ON DAY 491.383
EXPOSURE IN R 201.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 19

AVERAGE INITIAL READINGS :
GATE-SOURCE-VOLTAGE = 3.0027 ( .0092) V DIFF VOLTAGE = .0025 ( .0002) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 7
NUMBER OF DEVICES IN AVERAGE = 2

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.0667 ( .0012) | .5127 ( .0077) | 1.5540 ( .0089) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 7

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .004 | .9947 ( .0004) | .9893 ( .0141) | .9964 ( .0051) |
| .022 | .9931 ( .0004) | .9782 ( .0146) | .9980 ( .0054) |
| .080 | .9971 ( .0005) | .9918 ( .0146) | .9989 ( .0054) |
| .164 | .9974 ( .0006) | .9918 ( .0146) | .9992 ( .0056) |
| 1.013 | 1.0000 ( .0006) | 1.0000 ( .0150) | 1.0000 ( .0057) |
| 4.166 | 1.0084 ( .0008) | 1.0262 ( .0150) | 1.0025 ( .0060) |
| 29.067 | 1.1895 ( .0074) | 1.2377 ( .0141) | 1.1736 ( .0145) |
| 54.154 | 1.2321 ( .0118) | 1.2746 ( .0131) | 1.2181 ( .0201) |
| 62.072 | 1.2349 ( .0106) | 1.2858 ( .0126) | 1.2181 ( .0183) |
| 70.019 | 1.2407 ( .0109) | 1.2979 ( .0131) | 1.2218 ( .0189) |
| 102.014 | 1.2535 ( .0132) | 1.3062 ( .0116) | 1.2361 ( .0214) |
| 118.071 | 1.2504 ( .0133) | 1.2994 ( .0107) | 1.2343 ( .0213) |
| 133.012 | 1.2520 ( .0128) | 1.3057 ( .0141) | 1.2343 ( .0216) |

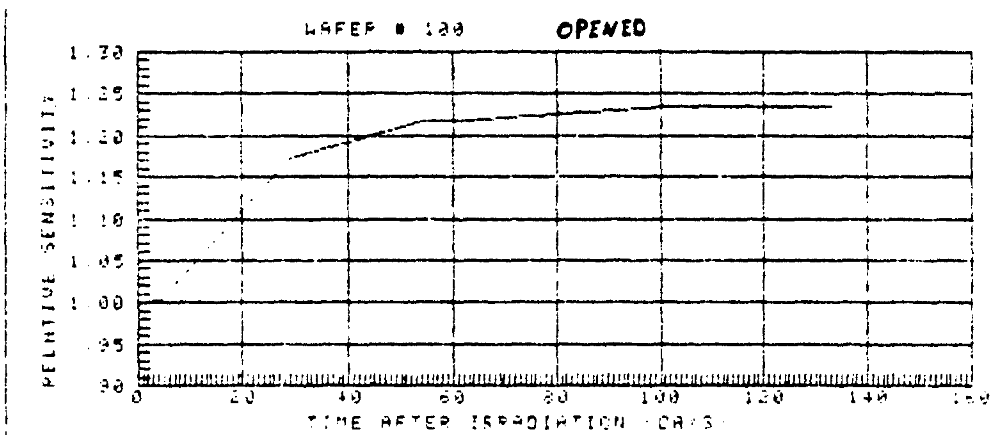


Figure 9: Measured sensitivity as a function of time after irradiation for devices packaged at Pantronics and irradiated 24 h after opening. The sensitivity is seen to closely resemble that of the sealed sensors in Figs 3 and 4.

6. The Effects of Pre-Irradiation Heating the Sensors

Heating the sensors to temperatures up to 400°C prior to irradiation made little difference to the response of those sensors packaged by Siltronics, but large changes were observed in the post-irradiation drift patterns of the sealed Pantronics-packaged sensors, depending on the magnitude and duration of the temperature. Heating these Pantronics-packaged sensors to 300°C for 10 to 20 min left them with about the same radiation characteristics as the Siltronics-packaged sensors, as seen by comparison of Fig 10 with Fig 5. Prolonged heating of these sensors restored them to their original radiation response. After opening the packages, pre-irradiation heating had no observable effect.

7. The Effect of Hydrogen on the Sensors

As part of an investigation of the photon energy response (see Sec. 9), some of the MOSFET chips were potted in various materials. It was noted that the post-irradiation drift of the Pantronics sensors in epoxy was modified considerably and showed the upward drift characteristic of those packaged by Siltronics. Diffusion of hydrogen from the epoxy into the gate oxide was suspected and, consequently, some sensors were tested after being exposed to hydrogen in a gaseous mixture of nitrogen and hydrogen. These, also, showed the upward post-irradiation drift when irradiated shortly after removal from the nitrogen/hydrogen mixture, as shown in Fig 11. This response is seen to be very similar to that for the sealed sensors of this type, shown in Fig 2, for the first day after irradiation, but the response of the unsealed sensors is seen to become about 10% less at later times.

It was also found that increases in the sensor readings were induced by inserting the sensors in the nitrogen/hydrogen mixture after irradiation. Fig 12 shows the sensitivity measurements for six devices from the second Mitel batch which had been opened before irradiation. The plot for device #1 represents three of these, which had been opened for three days, and device #5 represents the other three, which had been opened for only a few minutes. These devices were stored in a nitrogen/hydrogen mixture between days 27 and 36, during which the large jump in readings is seen to have taken place.

Thus indications are that the upward post-irradiation drift in the readings is related to the presence of hydrogen which modifies the trapping conditions. Heating may have the effect of redistributing the hydrogen in some of the sensor packages.

8. Response as a Function of Bias Voltage

Detailed measurements of radiation sensitivity as a function of gate-to-substrate voltage (bias voltage) were made using unheated sensors packaged by Pantronics. Results are plotted in Fig 13 for biases from -100 to +100 V using 24-h readings. Similar behavior was found for the sensors packaged by Siltronics but their response for positive bias was about 30% larger.

DRIFT IN RADIATION SENSITIVITY

BOARD# 4 WAFER# 100 THICKNESS .4 MICRON

INITIAL READING # 8 WAS ON DAY 363.440
IRRADIATION # 2 WAS ON DAY 363.459
EXPOSURE IN R 200.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.5
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 9

AVERAGE INITIAL READINGS :

GATE-SOURCE-VOLTAGE = 3.1240 ( .0614) V DIFF VOLTAGE = .0037 ( .0020) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 4
NUMBER OF DEVICES IN AVERAGE = 3

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.7106 ( .0080) | .6790 ( .0081) | 2.0316 ( .0027) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 4

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .003 | .8329 ( .0043) | .8616 ( .0110) | .8234 ( .0053) |
| .023 | .8813 ( .0050) | .8984 ( .0104) | .8756 ( .0063) |
| .083 | .9227 ( .0042) | .9345 ( .0117) | .9188 ( .0051) |
| .210 | .9542 ( .0027) | .9580 ( .0104) | .9530 ( .0036) |
| .910 | 1.0000 ( .0029) | 1.0000 ( .0120) | 1.0000 ( .0013) |
| 2.925 | 1.0259 ( .0059) | 1.0290 ( .0128) | 1.0249 ( .0036) |
| 6.944 | 1.0291 ( .0044) | 1.0383 ( .0130) | 1.0261 ( .0015) |
| 15.122 | 1.0263 ( .0043) | 1.0405 ( .0141) | 1.0215 ( .0011) |
| 44.976 | 1.0111 ( .0048) | 1.0368 ( .0143) | 1.0025 ( .0017) |
| 69.092 | 1.0051 ( .0092) | 1.0312 ( .0144) | .9964 ( .0075) |
| 83.113 | .9935 ( .0057) | 1.0263 ( .0158) | .9826 ( .0027) |
| 124.991 | .9886 ( .0086) | 1.0277 ( .0153) | .9756 ( .0064) |
| 162.096 | .9838 ( .0066) | 1.0511 ( .0160) | .9613 ( .0039) |
| 239.994 | .9727 ( .0067) | 1.0324 ( .0148) | .9528 ( .0046) |

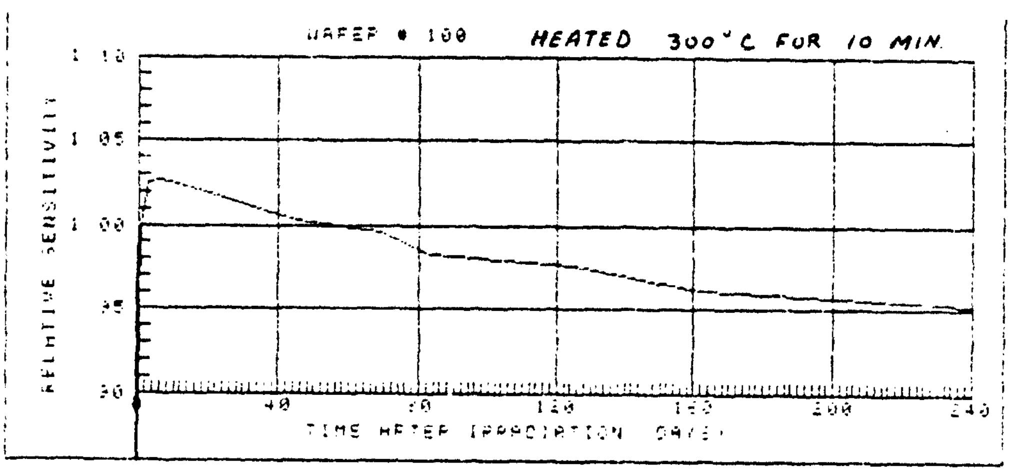


**Figure 10: Measured sensitivity as a function of time after irradiation for devices packaged by Pantronics and heated for 10 min at 300°C prior to irradiation. Note the similarity to the response of the Siltronics-packaged devices from the same Mitel run as seen in Figure 5.**

DRIFT IN RADIATION SENSITIVITY

BOARD# 35 WAFER# 17 THICKNESS .4 MICRON

INITIAL READING # 21 WAS ON DAY 462.405
IRRADIATION # 2 WAS ON DAY 462.417
EXPOSURE IN R 207.0
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 22

AVERAGE INITIAL READINGS :

GATE-SOURCE-VOLTAGE = 2.9569 ( .0319) V DIFF VOLTAGE = .0033 ( .0030) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 35
NUMBER OF DEVICES IN AVERAGE = 6

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.5366 ( .0329) | .6417 ( .0156) | 1.8948 ( .0188) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 35

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .003 | .9323 ( .0047) | .8820 ( .0106) | .9494 ( .0033) |
| .009 | .9427 ( .0071) | .8933 ( .0140) | .9595 ( .0054) |
| .026 | .9582 ( .0102) | .9155 ( .0174) | .9727 ( .0081) |
| .074 | .9775 ( .0129) | .9474 ( .0211) | .9877 ( .0105) |
| .191 | .9920 ( .0147) | .9734 ( .0238) | .9984 ( .0120) |
| .899 | 1.0000 ( .0130) | 1.0000 ( .0243) | 1.0000 ( .0099) |
| 1.945 | .9908 ( .0106) | 1.0041 ( .0235) | .9863 ( .0075) |
| 5.016 | .9902 ( .0080) | 1.0243 ( .0229) | .9787 ( .0049) |
| 13.112 | .9804 ( .0069) | 1.0166 ( .0210) | .9681 ( .0066) |
| 20.964 | .9761 ( .0059) | 1.0226 ( .0238) | .9603 ( .0084) |
| 26.149 | .9668 ( .0074) | 1.0211 ( .0239) | .9484 ( .0075) |
| 33.189 | .9624 ( .0064) | 1.0204 ( .0216) | .9427 ( .0076) |
| 41.976 | .9623 ( .0056) | 1.0255 ( .0207) | .9409 ( .0099) |
| 55.148 | .9587 ( .0065) | 1.0325 ( .0205) | .9338 ( .0094) |
| 141.180 | .9531 ( .0065) | 1.0287 ( .0190) | .9275 ( .0127) |

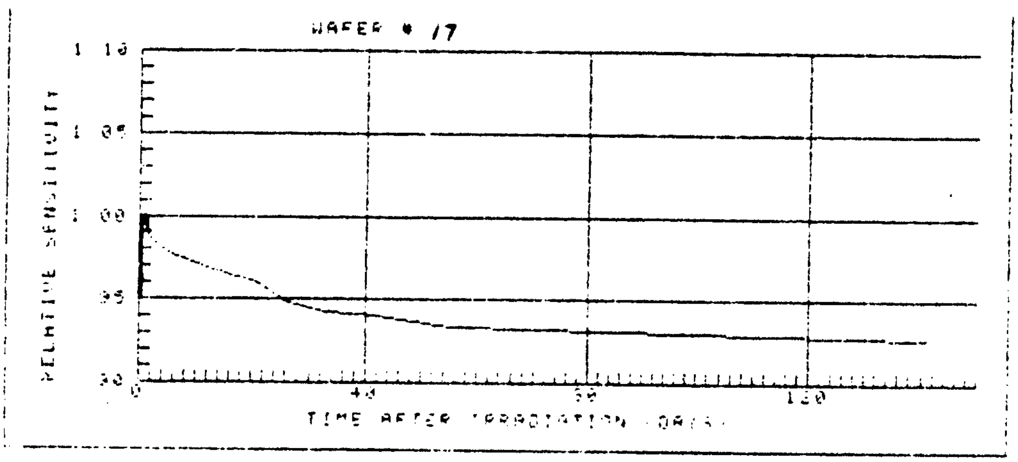


**Figure 11: Measured sensitivity as a function of time after irradiation for devices from the first Mitel batch which had been left unsealed and which had been stored in a nitrogen/hydrogen mixture for the 21 h preceeding irradiation. Note the agreement with the response of the sealed devices of Figure 2 for the first day and the differences in the drift patterns at later times.**

DRIFT IN RADIATION SENSITIVITY

BOARD# 18 WAFER# 119 THICKNESS .4 MICRON

INITIAL READING # 2 WAS ON DAY 468.419
IRRADIATION # 1 WAS ON DAY 468.438
EXPOSURE IN R 200.5
RATE IN R/H 1000.0
BIAS IN VOLTS 5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS # 3

AVERAGE INITIAL READINGS :

GATE-SOURCE-VOLTAGE = 2.7888 ( .0573) V DIFF VOLTAGE = .0019 ( .0030) V

AVERAGE SENSITIVITY IN MV/R 24 H AFTER IRRADIATION FOR BOARD # 18
NUMBER OF DEVICES IN AVERAGE = 6

| BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|
| 2.4320 ( .2590) | .6146 ( .0607) | 1.8174 ( .1984) |

AVERAGE SENSITIVITY RELATIVE TO 24-H SENSITIVITY FOR BOARD # 18

| DAYS AFTER IRRAD | BIASED SIDE | UNBIASED SIDE | DIFFERENTIAL |
|---|---|---|---|
| .002 | .9288 ( .0618) | .9124 ( .0787) | .9344 ( .0562) |
| .009 | .9439 ( .0701) | .9313 ( .0855) | .9482 ( .0649) |
| .050 | .9757 ( .0880) | .9692 ( .0910) | .9779 ( .0871) |
| .113 | .9860 ( .0963) | .9834 ( .0940) | .9870 ( .0972) |
| .969 | 1.0000 ( .1065) | 1.0000 ( .0987) | 1.0000 ( .1092) |
| 7.094 | 1.0144 ( .0788) | 1.0285 ( .0699) | 1.0096 ( .0819) |
| 14.945 | 1.0277 ( .0569) | 1.0457 ( .0587) | 1.0216 ( .0564) |
| 20.126 | 1.0327 ( .0509) | 1.0484 ( .0550) | 1.0273 ( .0497) |
| 27.112 | 1.0343 ( .0403) | 1.0548 ( .0525) | 1.0274 ( .0365) |
| 35.945 | 1.2255 ( .0198) | 1.2171 ( .0146) | 1.2284 ( .0289) |
| 35.996 | 1.2163 ( .0170) | 1.2214 ( .0164) | 1.2146 ( .0259) |
| 36.155 | 1.2097 ( .0152) | 1.2196 ( .0180) | 1.2063 ( .0240) |
| 36.952 | 1.2039 ( .0156) | 1.2169 ( .0159) | 1.1994 ( .0234) |
| 38.222 | 1.1983 ( .0150) | 1.2160 ( .0127) | 1.1923 ( .0230) |
| 42.934 | 1.1907 ( .0151) | 1.2148 ( .0149) | 1.1826 ( .0222) |
| 43.943 | 1.1870 ( .0144) | 1.2080 ( .0171) | 1.1799 ( .0218) |
| 47.947 | 1.1864 ( .0143) | 1.2154 ( .0161) | 1.1765 ( .0217) |

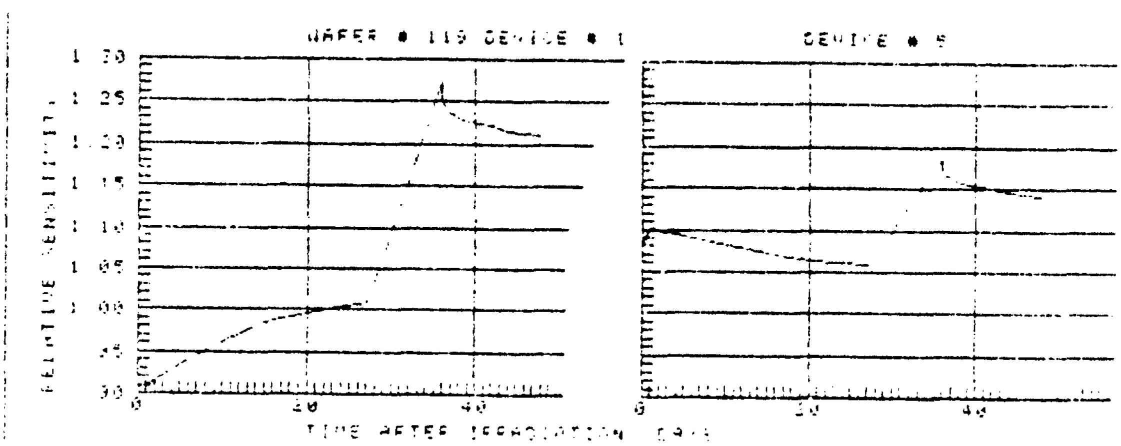


**Figure 12: Measured sensitivity as a function of time after irradiation for devices from the second Mitel batch which had been opened before irradiation. Device #1 was opened 3 days before irradiation and device #5 for only a few minutes. These devices were stored in a nitrogen/hydrogen mixture between days 27 and 36. Large increases in the readings are seen to have taken place during this period.**

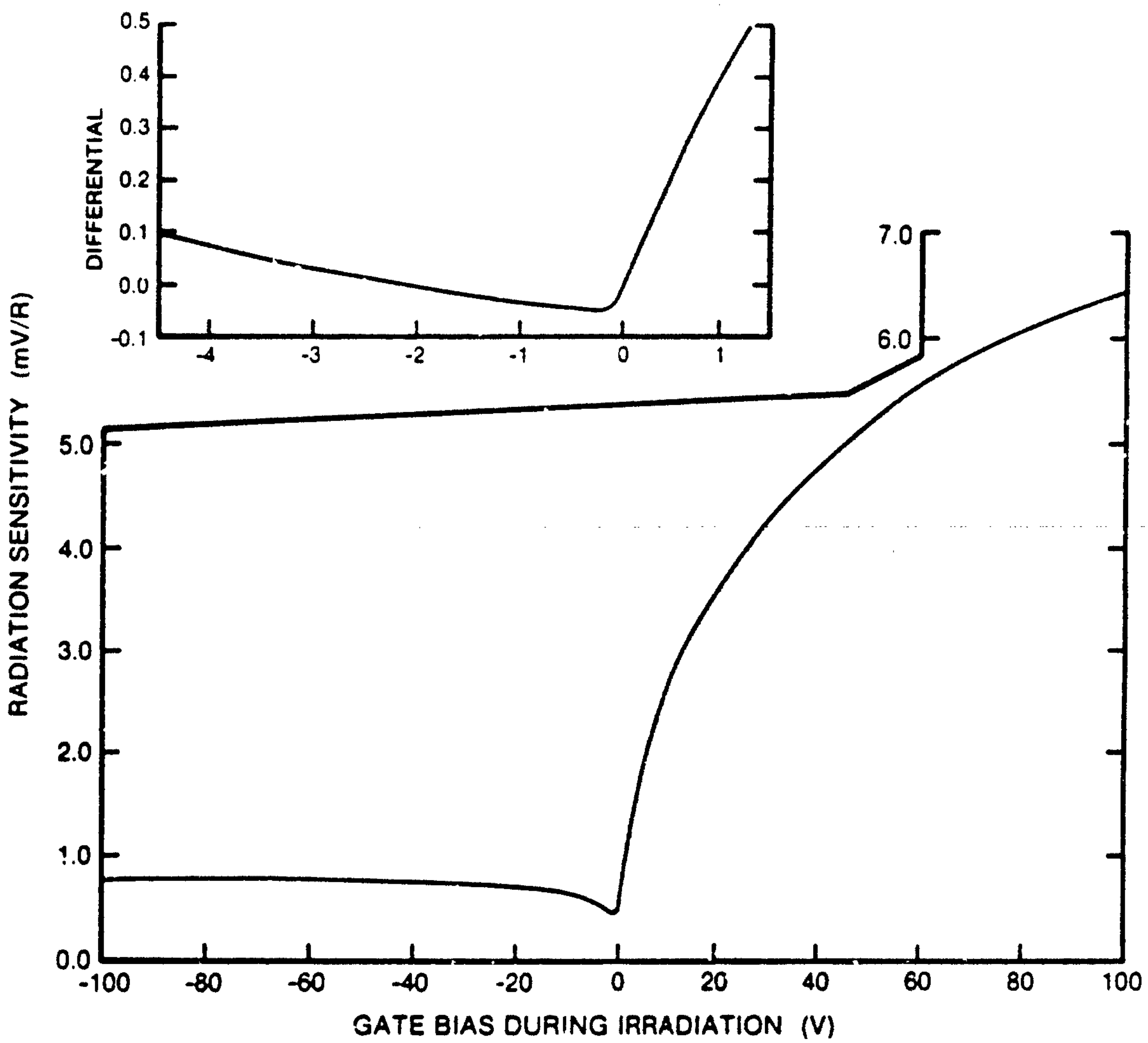


Figure 13: Radiation sensitivity as a function of gate bias during irradiation for sensors packaged by Pantronics. Readings were taken 24 h after exposure to 200 R of $^{60}Co$. The detailed differential response shows that the minimum response occurs at a small negative voltage.

The sensitivity/bias relationship can be explained by accepted models of the MOSFET (Ref (13)). Low sensitivity at zero bias can result from the recombination of the holes and electrons produced by the ionizing particles. The application of a voltage during irradiation establishes an electric field which separates the charged particles, reducing recombination and removing some of the charged particles from the oxide. The electrons, which have a higher mobility than the holes, should be more readily removed.

A positive bias on the gate causes the holes to migrate toward the $Si/SiO_2$ interface at the silicon chip where there is a high concentration of hole traps. Charges trapped near this interface are more effective in causing a shift in the gate-to-source operating voltage, since this shift is proportional to the distance of the trapped charged from the gate. Thus, the positive bias can lead to a relatively large radiation sensitivity. The application of a negative voltage leads to relatively low radiation sensitivity by reducing recombination and by causing the holes to drift toward the gate.

There may also be some negative-charge trapping but, evidently, the positive-charge trapping always predominates for these devices since, even with a negative bias, the gate-to-source operating voltage is always observed to increase as a result of irradiation.

The maximum theoretical shift in voltage can be calculated on the assumption that all the positive charge produced by the ionization is trapped at the chip interface and that all the negative charge is removed. This shift is given by

$$\Delta V = \Delta Q/C, \tag{1}$$

where $\Delta Q$ is the number of electron-hole pairs produced per unit area and C is the gate capacitance per unit area. For a dose D in $SiO_2$ of thickness x

$$\Delta Q = D\,\rho\,xe/W, \tag{2}$$

where $\rho$ is the density of $SiO_2$, e is the electronic charge and W the energy required to produce an electron-hole pair in $SiO_2$ (W/e is the energy in eV). C can be taken as $\varepsilon k/x$ where $\varepsilon$ is the dielectric constant of $SiO_2$ and k the permitivity of free space. $\Delta V/D$ becomes

$$\Delta V/D = \rho x^2 e/W\varepsilon k \tag{3}$$

Using $\rho = 2.3 \times 10^3$ kg/m$^3$, $x = 4 \times 10^{-7}$ m, W/e = 18 eV and $\varepsilon = 3.9$, $\Delta V/D = 0.59$ V/Gy = 5.9 mV/cGy.

Measurements were made in terms of exposure X in Roentgens (R). (For $^{60}$Co, 1 R is equivalent to about 0.96 cGy (tissue)). As discussed in Sec. 9, indications are that the dose per unit exposure for these sensors in the present packages is about 1.1 cGy (oxide)/R. This gives $V/X = 6.5$ mV/R or $V/D = 6.8$ mV/cGy (tissue) for the maximum values. Comparison of this value with the responses found for these sensors indicates that the above conditions for maximum voltage shift exist at large positive bias.

For the Siltronics-packaged sensors, which have an upward post-irradiation drift in reading, the increase in gate-to-source voltage was found to increase with increasing positive irradiation bias, although the increase in terms of dose became smaller. It was also noted that the post-irradiation drift was not strongly dependent on the gate bias maintained after irradiation. The upward drift remained much the same with the post-irradiation bias at +5.6 or -5.6 V. These results tend to negate the theory that this drift may be related to detrapping of positive charge in the bulk of the oxide and retrapping closer to the silicon chip, since the negative voltage should cause the holes to drift in the other direction.

Detrapping of negative charge could explain the upward post-irradiation drift, assuming that the detrapped electrons are removed from the oxide by an electric field or by diffusion. This explanation requires a fairly large fraction of negative-charge trapping even at the higher electric fields used. Possibly the higher concentrations of hydrogen in the oxide serve to promote negative-charge detrapping.

## 9. The Effect of Packaging on the Photon-Energy Response

Sensors packaged by both manufacturers showed similar energy response as described above for sensors from the first production run. To study the effects of the packaging material, such as the gold plating on the contacts near the MOSFET chip, some of the chips, mounted on the base of the packages, were potted with other materials, including epoxy, paraffin wax, silicone and alumina. These materials were found to reduce the response at energies between 100 and 200 keV. In addition, the epoxy and, to a lesser extent, the paraffin were found to enhance the post-irradiation drift in reading.

At $^{60}$Co energy, the paraffin and silicone reduced the response by about 13%. Fine grains of alumina covering the chip reduced the response by about 8%. The reduction for epoxy could not be measured conclusively because of the large post-irradiation drift with that potting material.

The response to x-rays relative to $^{60}$Co gammas is shown in Table I for Pantronics-packaged sensors in their normal (opened) packages and after potting in epoxy. The energies listed are median energies for filtered x-ray spectra with FWHM of about 50% of the median energy. The epoxy is seen to be very effective in flattening the energy response such that sensors potted in this material would require little or no photon filtration.

Measurements with the other potting materials were done with only one x-ray energy and $^{60}Co$ gammas. Siltronics-packaged sensors were used for this purpose. The results are given in Table II which includes ratios of the response to x-rays and $^{60}Co$ gammas for the normal packages and for some packages with the usual ceramic lid replaced by other materials.

Table I

Pesponse of Normal and Epoxy-Potted Sensors to X-Rays Relative to Their Response to $^{60}Co$ Gamma Rays. Irradiation Was Normal to the Main Surfaces of the Chip from Either the Front or Back

| X-Ray Energy | Normal Front | Normal Back | Epoxy Front | Epoxy Back |
|---|---|---|---|---|
| 100 KeV | 3.4 | 2.9 | 1.07 | 1.04 |
| 135 KeV | 2.6 | | 0.94 | |
| 165 KeV | 2.20 | 2.24 | 1.08 | 0.84 |
| 200 KeV | 1.77 | | 0.92 | |

Table II

Response of Sensors to 135 (or 140)-keV X-Rays Relative to $^{60}Co$ Gamma Rays

| X-Ray Energy | Package Type | Package Modifications | Response Ratio Front | Response Ratio Back |
|---|---|---|---|---|
| 135 | Ceramic | None | 2.7 | 2.6 |
| 140 | Ceramic | None | 2.6 | 2.8 |
| 140 | Ceramic | Aluminum Lid | 2.1 | |
| 140 | Ceramic | Tin Lid | 9 | |
| 140 | Ceramic | Clear Sapphire Lid | 2.1 | |
| 140 | Ceramic | Polyethylene Lid | 1.6 | |
| 135 | Ceramic | Kapton Lid | 1.8 | |
| 135 | Ceramic | Silicon Grease Potting | 1.14 | 1.02 |
| 135 | Ceramic | Paraffin Wax Potting | 1.04 | 0.90 |
| 135 | Ceramic | Granular Alumina Potting | 1.09 | 0.97 |
| 135 | Cerdip | None | 2.6 | |
| 135 | Cerdip | Epoxy | 0.94 | |

As seen in Table II the response for these x-rays relative to $^{60}Co$ is between 2.5 and 3 for the normal packages. Replacing the normal lid of the ceramic package (with its glass bead for sealing) with sapphire (which is also $Al_2O_3$), aluminum, polyethylene or Kapton leads to a considerable reduction in response. There is a further reduction when the open volume around the chip is completely filled, the three potting materials all being effective at this energy. The alumina poured around the chip is more inert than the other materials and does not induce a post-irradiation drift in the readings. However, this type of potting might be difficult to implement on a large scale.

Measurements were made using a tin lid to demonstrate the effect of a high-Z material. It can be presumed that photoelectron and x-ray scattering from gold plating in the package and from lead in the sealing glass are responsible for the large response observed for x-irradiations of sensors in the unmodified ceramic and cerdip packages used by Siltronics and Pantronics. A more suitable package is being considered for future sensors.

## 10. Dose-Rate Response

As stated in Sec. 3, the response of the biased side of these sensors is reduced at very high dose rates and it has been concluded that this was related to a drop in bias voltage during the radiation pulse. It was suggested in Ref (11) that this could be due, in part, to conductivity in the nitrogen gas in the sealed packages and that sensors in another atmosphere, such as air in which the electron lifetime is short, might show a lesser dose-rate effect. However, more recent measurements have shown that both sealed and unsealed sensors have similar degradation in response when irradiated at the very high dose rates from a pulsed x-ray source. Measurements were made with the 6-MeV pulsed x-ray source at Aberdeen Proving Ground using a dose of approximately 5 Gy in a single 80-ns pulse. The sensors were connected as shown in Fig 14 using a bias voltage E of 5.6 V and biasing resistors R of 1 M ohm. Half of the sensors had a 1-nF capacitor C added between the biased gate and the substrate, but no capacitance was added to the unbiased gates. The average values for seven or eight sensors, about half of which were sealed, are listed in Table III which gives the response to the x-ray pulse relative to the response to $^{60}Co$ gamma rays.

The response of the unbiased gate was observed to be high for the x-ray pulse relative to $^{60}Co$. This was not altered by potting the sensor chip in alumina or epoxy indicating that the high response is not due to the high response of a low-energy component of the x-ray spectrum. Maier and Tallon (14) have shown that at very high dose rates photovoltaic effects can cause the generation of a positive bias in this type of device which could explain this sensitivity enhancement. As seen from Table III, the addition of a 1-nF capacitor gave a large improvement in the response of the biased gate but the differential response to the x-ray pulse remained 20% lower than for $^{60}Co$. Further investigation of this problem is required and should be carried out using the MOSFET in its dosimeter package.

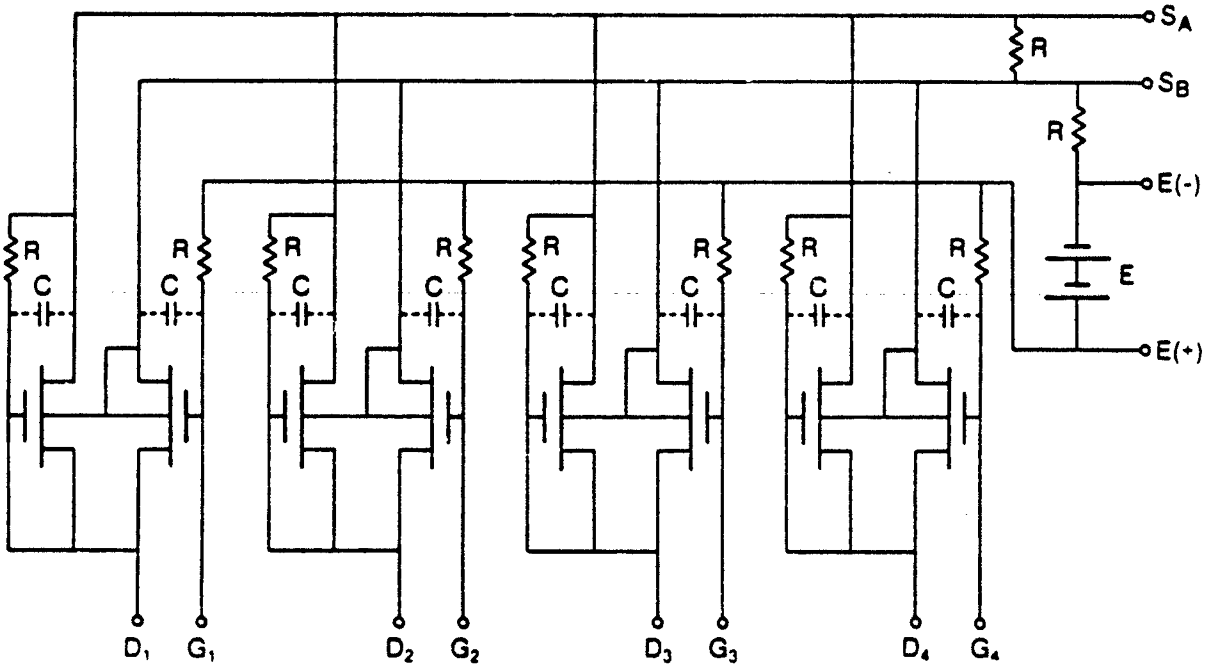


Figure 14: Circuit diagram of biasing arrangement used in testing the response to pulsed x-rays. This simulates a practical circuit in a dosimeter locket.

TABLE III

Radiation Sensitivity of MOSFET Sensor to Pulsed X-Ray Source Relative to $^{60}Co$ Source. Note the Increase in Response when the Capacitor Is Added between the Biased Gate and the Substrate

| Added Capacitance (nF) | | Relative Sensitivity | | |
|---|---|---|---|---|
| Unbiased | Biased | Unbiased | Biased | Differential |
| 0 | 0 | 1.25 | 0.45 | 0.2 |
| 0 | 1 | 1.25 | 0.9 | 0.6 |

## 11. Summary and Conclusions

Comparison of measurements of MOSFET sensors from the two production batches at Mitel shows that there is a significant difference in the response of the two batches as measured at various times after irradiation. This may be related to differences in fabrication procedure which should be identified and optimized for most consistent response.

Significant differences in performance of the MOSFET sensors were also observed to be related to differences in the packages and/or packaging procedures of Siltronics and Pantronics. The sensors packaged at Siltronics showed more consistent behaviour and less total drift in reading following irradiation, although the Pantronics-packaged sensors frequently gave very constant readings for several days after irradiation.

The general upward post-irradiation drift in readings, which is independent of the post-irradiation bias, indicates the removal of trapped negative charge rather than the relocation of trapped positive charge. This reading drift appears to be related to the presence of hydrogen which presumably diffuses into the oxide layer.

The reduction in response to photons of energy 100 to 200 keV, which results from potting the sensor chip, strongly suggests that much improved energy response can be obtained by using a package without any high-Z materials near the sensitive volume of the MOSFET.

While the high dose-rate response appears to be alleviated by using a capacitor to help maintain the gate bias, further investigation of this problem is required using the final dosimeter package.

## 12. References

1. W.J. Poch and A.G. Holmes-Siedle, RCA Engineer 16 (3) 56 (1970).

2. D.R. Ciarlo, R. Kalibjian, K. Mayeda and T.A. Boster, "Metal-Oxide-Semiconductor X-Ray Detectors", IEEE Trans. Nucl. Sci, NS-19, No. 1, 350 (1972).

3. D.R. Ciarlo, "MOSFET Detector Evaluation", IEEE Trans. Nucl. Sci. NS-21, 390 (1974).

4. A. Holmes-Siedle, "The Space-Charge Dosimeter", Nucl. Instr. and Methods, 121, 169 (1974).

5. S. McGowan, "The Metal Oxide-Semiconductor Field-Effect Transistor (MOSFET) as a Military Personal Dosimeter", DREO TN 72-26 (1972).

6. I. Thomson, "Evaluation of MOSFET Radiation Sensors", Canadian Astronautics Limited Report No. IDRT-240-007 (1983).

7. J.M. Sanders and V. Baldur, "Sensor Test Report", Canadian Astronautics Limited Report No. DOSII. 291.5 (1985).

8. S. McGowan, "Evaluation of Dual MOSFET Gamma-Radiation Sensors Fabricated by Carleton University", DREO TN 86-4 (1985).

9. G. Roberts, "Dual MOSFET Dosimeter", Pacific Microcircuits Limited Report (1986).

10. S. McGowan, "Sensitivity of MOSFET Radiation Sensors from the First Production Run at Mitel Corporation", DREO Unpublished Report.

11. S. McGowan, "Response of MOSFET/n-Diode Dosimeters to the Very High Dose Rates from the Pulsed Radiation Sources at Aberdeen Proving Ground", DREO Unpublished Report.

12. S. Kronenberg, "Back-Scattered Rutherford Electrons", to be published.

13. R. Freeman and A. Holmes-Siedle, "A Simple Model for Predicting Radiation Effects in MOS Devices", IEEE Trans. Nucl. Sci., NS-25, No. 6, 1216 (1978).

14. R.J. Maier and R.W. Tallon, "Dose-Rate Effects in the Permanent Threshold Voltage Shifts of MOS Transistors", IEEE Trans. Nucl. Sci., NS-22, No. 6, 2214 (1975).